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Published in:
International Journal of Sustainable Energy Planning and Management

DOI (link to publication from Publisher):
10.5278/ijsepm.3683

Publication date:
2020

Document Version
Publisher's PDF, also known as Version of record

International Journal of Sustainable Energy Planning and Management Vol. 27 2020 17–34

International Journal of
Sustainable Energy Planning and Management

The role of 4th generation district heating (4GDH) in a highly electrified hydropower dominated energy system – The case of Norway

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ABSTRACT

District heating (DH) is considered an important component in a future highly renewable European energy system. With the turn towards developing 4th generation district heating (4GDH), the integral role of district heating in fully renewable energy systems is emphasized further. Norway is a country that is expected to play a significant role in the transition of the European energy system due to its high shares of flexible hydropower in the electricity sector. While the country is moving towards electrification in all sectors and higher shares of variable renewable electricity generation, district heating could potentially decrease the need for electric generation and grid capacity expansion and increase the flexibility of the system. In this paper we investigate the role of 4GDH in a highly electrified future Norwegian energy system. A highly electrified scenario for the Norwegian energy system is constructed based on a step-by-step approach, implementing measures towards electrification and expansion of renewable electricity generation. Then, a 4GDH scenario is constructed for the purpose of analysing the role of 4GDH in a highly electrified hydropower based energy system. EnergyPLAN is used for simulation. Results show that an expansion of 4GDH will increase the total system efficiency of the Norwegian energy system. However, the positive effects are only seen in relation to the introduction of efficiency measures such as heat savings, more efficient heating solutions and integration of low-temperature excess heat. Implementation of heat savings and highly efficient heat pumps in individual based heating systems show a similar effect, but does not allow for excess heat integration. In the modelled DH scenario, the introduction of large heat storages has no influence on the operation of the energy system, due to the logic behind the EnergyPLAN model and the national energy system analysis approach chosen, and thus the effect of implementing 4GDH may be underestimated.

Keywords:

Hydropower;
4GDH;
Smart energy systems;
Electrification;
Energy system analysis;

URL: http://doi.org/10.5278/ijsepm.3683

1. Introduction

The energy history of Norway is largely the history of hydropower development, and today, the electricity and heating sectors are more or less monopolized by hydropower [1]. Almost 100% of the electricity used in the country is from hydropower, and unlike many other countries, a large degree of the energy used for heating is based on electricity. In 2016, 143 TWh of electricity was produced by hydropower plants, covering 108% of the electricity demand in the country, thus making Norway a net exporter of electricity [2]. The Norwegian Water Resources and Energy Directorate (NVE) estimates that the surplus electricity production in Norway in a normal year will increase even further in the future, from 5 TWh/year in 2018 to 20 TWh/year in 2030 [3]. This is based on assumptions of a large expansion of

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wind power capacity as well as an increased inflow to hydropower plants going towards 2030 [3]. Between 2010 and 2016, installed wind power capacity increased by 186%, increasing the total installed wind power capacity to 1,207 MW in 2017 [4]. This has increased and is expected to increase further in the coming years, and per November 2019 the installed capacity was 2,128 MW [5]. The expansion of wind power capacity has also been source of great debate in Norway in 2019 with the completion of NVE's suggestion for a national framework for wind power from April 2019 [6]. Negative comments and reactions dominated the consultation responses and the national framework has since been abandoned by the government [7].

Even though Norway has an electricity surplus that is expected to increase, it is also the country with the second highest electricity consumption per capita, in the world, according to The International Energy Agency (IEA) [8]. Of the net electricity consumption in the country, 42.4% is used in the industry sector, 34.1% in households and agriculture, and 23.5% in service sectors [9]. The electricity demand is expected to increase even further in the future with the introduction of electric vehicles, electrification of industrial and maritime sectors, as well as the potential increase of electricity use in large data centres [10]. An increased electrification will not only affect the yearly electricity demand in the country, but also the hourly load and the loads in the electricity network, if regulation and efficiency measures on the demand side are not implemented.

The Norwegian hydropower resources consist largely of dammed hydropower facilities with substantial storage capacity connected. In the transition towards renewables in Europe, there is also a debate concerning the technical and economic potential of using hydropower resources to balance fluctuations in the European electricity grid [11]. This solution is dependent on both the capacity of electricity producing units in the country, storage capacity, and interconnectors to Europe. Using the Norwegian hydropower resources as a «green battery» for Europe would in most cases require a significant expansion of interconnector cables, representing some investment risk for Norway. For this reason, it has been commented that the necessary expansion will probably develop slowly following the development in Europe [11].

A large share of hydropower based electric heating in the Norwegian heating sector means that this sector has a low CO_2 footprint, if not taking into account the potential marginal electricity production outside the Norwegian energy system boundary. However, other solutions, such as heat pumps and modern district heating systems, may be more efficient. An expansion of district heating in the country can therefore increase the system efficiency of the energy system, increasing the expected electricity surplus or reducing the need for electricity production capacity expansion, and electric grid capacity. A reduced inland electricity demand can also enable more export of renewable electricity to Europe, potentially supporting the decarbonisation of the energy sector in other countries. Furthermore, district heating systems can take advantage of economies of scale, higher efficiencies and centralised control to add flexibility to the energy system [3, p 47].

1.1. Status of District heating in Norway

In 2016, there were 107 district heating companies and district heating could be found in parts of all counties except one [13,14]. However, the Norwegian heating sector is still largely dominated by electric heating. It is assumed that 35.2 TWh was used for direct electric heating in buildings in 2016 [10]. In addition, 3.7 TWh electricity was used for electric heat pumps [10]. This does not include electricity use and heat pumps in the district heating sector. In 2018, the amount of district heating delivered to consumers was 5.7 TWh [15]. Of this, 78.3% was delivered to industry and service sectors, with the service sector accounting for as much as 61.9% of the total heat delivered [15].

The potential of district heating, as a way to combine increased use of waste heat, excess heat and renewable heat resources, has been highlighted at several occasions [16]. The White Paper from 1999 concerning Norwegian energy politics included a goal of increasing water based heating based on renewable energy sources, heat pumps and excess heat by 4 TWh by 2010 [17]. District heating was mentioned as a solution mostly relevant in densely populated areas [17]. In a new White Paper regarding energy politics published in 2016, it was stated that:

District heating works well with the energy supply. If district heating can replace energy use in the winter, this can limit the need for investments in the energy system [3, p. 47].

Thus, it is clear that national authorities have an idea of the potential of integrating district heating in the Norwegian energy system. However, none of the documents assessed have included any explicit goals concerning district heating.

1.2. Energy system and district heating analyses for Norway

The potential and future role of district heating in Norway has until now only been analysed to a limited extent. Comprehensive studies of a full transition to 100% renewable energy with a high share of electrification in all Norwegian energy sectors, including an assessment of the future potential district heating therein, could not be identified by the authors. The majority of the previous research focusses either on specific energy sources, energy technologies, or geographic areas in relation to district heating. A few studies have documented scenarios for the entire Norwegian energy system, or larger parts thereof.

One group of studies has been concerned with improving the environmental profile of the heating sector, often with a particular focus on the introduction of traditional or new bioenergy technologies, which are sometimes seen as an adequate fuel source for district heating [18–20]. National, geographic assessments of district heating potentials are only slowly beginning to emerge, and seem to be limited to specific resource assessments, for instance, industrial excess heat potentials [21]. The existence of comprehensive heat atlases (cf. [22,23]) that allow for synergetic analyses of heat demand reduction and supply potentials has largely been missing for Norway up until now. However, Norway is included in the Hotmaps tool presented in [24]. In [25] Grundahl & Nielsen have investigated the accuracy of heat atlases compared to measured data in Denmark and found that the atlas analysed had accurate estimations for single-family households but were quite uncertain in the predictions for other building categories, such as flat buildings and service sector buildings. However, such atlases may provide a starting point for analyses of DH.

Other studies focus on district heating at different scales or on specific, new DH concepts [16,26,27]. From the perspective of 4GDH, Norwegian analyses of new district heating concepts are beginning to emerge. In [28] the authors find that increasing the flexibility and adoption of Power-to-heat (P2H) solutions in district heating plants is highly dependent on low future electricity prices. Idsø and Årethun [29] describe a Water-thermal Energy Production System (WEPS) based on large heat pumps as well as individual heat pumps using fjord water as the heat source. It is reported that WEPS with large heat pumps in a heat centre supplying a group of houses with heat is more cost-efficient than a WEPS using many individual heat pumps [29].

In [30], Sandberg et al. analyse framework conditions for DH in the Nordic countries and evaluate the effects of varying framework conditions on a model DH plant in Norway, Sweden, Denmark and Finland. Their conclusions are that there are only small differences in profitability of DH between the countries, and that the reasons for differences in prevalence of DH in the Nordic countries are mainly related to differences in infrastructure and local commitment. For Norway specifically, it is concluded that electricity is competitive in both DH and individual heating sectors [30].

A study by one of the authors of this paper has investigated the role of district heating in the Norwegian energy system as it was in 2015, and concluded that an expansion of district heating could free up power capacity within hours, which in turn could increase the potential flexibility of Norwegian hydropower resources in a European context. However, the study did not take into account potential electrification and transitions of the Norwegian energy system going forward [31].

1.3. 4th generation district heating and smart energy systems

An increasing number of studies in Europe and beyond focuses on the development of 4GDH and smart energy systems. According to the smart energy systems literature, a «smart energy system is defined as an approach in which smart electricity, thermal and gas grids are combined with storage technologies and coordinated to identify synergies between them in order to achieve an optimal solution for each individual sector as well as for the overall energy system» [32]. The focus on total energy system efficiency and complete phase out of fossil fuels in all energy sectors distinguishes the smart energy system approach from other approaches such as smart grids, where the focus is on resolving production and demand imbalances within the electricity sector only (cf. [33]). At the same time, smart energy system analyses focus on finding optimal balances between energy demand reductions and energy supply investments [34,35] and have paid special attention to the role of thermal grids [36], adequate storage solutions [37], as well as biomass resource limitations and alternative fuels for heavy duty transport [38,39].

Smart thermal grids as important, integral parts of smart energy systems are to a large extent epitomized by 4GDH. The concept of 4GDH systems has been a popular research topic in recent years. A status of the mentioning of the concept in literature was made by Lund et al. in [40], which showed an increasing number of scientific literature mentions from 2014 until 2017. In 2014, Lund et al. defined the concept of 4GDH as a "[…] coherent technological and institutional concept, which by means of smart thermal grids assists the appropriate development of sustainable energy systems. 4GDH systems provide the heat supply of low-energy buildings with low grid losses in a way in which the use of low-temperature heat sources is integrated with the operation of smart energy systems. […]" [41]. 4GDH represents a cost-effective and fuel efficient pathway towards complete decarbonisation of the heating sector, as demonstrated in Denmark [36] and the Baltic countries [42]. In Sweden and Finland, too, district heating is a major component of the energy system and it is being discussed how 4GDH elements can be integrated further into the heating sectors of the two countries [43–46]. At the level of the EU, research projects such as Heat Roadmap Europe have analysed how 4GDH thinking can lead to an increased and more efficient utilization of district heating in the majority of European countries [36,47–50].

According to the two related perspectives of smart energy systems and 4GDH, district heating networks can play a central role in energy systems based on large amounts of renewable energy due to their ability to i) integrate fluctuating renewable electricity through e.g. power-to-heat (P2H) solutions; ii) at the same time, or additionally, make use of low-temperature heat sources, such as ground-source heat, solar thermal energy or low-temperature excess heat from industry and service sectors; iii) on the basis of ii) support and necessitate the reduction of the heat demand in the building mass through e.g. energy-efficient refurbishment; and iv) continue to support the operation of flexible production units, such as combined heat and power (CHP) units, especially in combination with heat storages. Thus, it has been shown that 4GDH can facilitate the implementation of 100% renewable energy systems by increasing the flexibility, supply security and fuel efficiency of these systems. [36,40,51–55].

1.4. Future potential of district heating in Norway

How district heating will develop in the future will largely depend on national regulations. Still, there is no doubt that the Norwegian energy system faces substantial changes related to increased electrification and increased penetration of variable renewable electricity generation in the system [3]. In this transition, district heating could take some of the strain off the system [30].

The potential for expansion of district heating in Norway has been evaluated in different reports. In [56], the authors estimated a DH potential between 4.6 TWh and 6.6 TWh towards 2015, based on concrete plans and dependent on framework conditions. The actual district heating delivered in 2015 amounted to 5.5 TWh, thus much of this potential estimated had been realised. In [57] a technical potential of 11.5 TWh towards 2020 and 2030 was identified. This included only buildings that already had a waterborne heating system or were expected to get one installed in relation to renovation works. A market potential of 6.8 TWh in 2020 and 5.3 TWh in 2030 for coalescing of existing district heating, in addition to existing demands of 3.2 TWh, was found by the authors in [58]. Thus, a total potential of 10 TWh and 8.5 TWh in 2020 and 2030 respectively may exist.

1.5. Scope and article structure

Based on the status and challenges presented in the introduction, the scope of the analysis presented in this article can be summarised as follows:

To what extent can the introduction of 4GDH support a further electrification and development of a smart energy system in Norway, and how does this affect the potential electricity surplus?

To answer this, a national energy system analysis for Norway using the simulation tool EnergyPLAN is conducted. Using a 4-step approach, a highly electrified reference scenario is constructed as basis for the analysis, with a 2016-model being the starting point. A scenario representing a 4GDH scenario in the context of a smart energy system is constructed, simulated and compared to the reference scenario for what concerns electricity demands, production and surplus. A separate analysis concerning excess heat is conducted within the constructed 4GDH scenario. Finally, the constructed DH scenario is compared to an alternative highly efficient individual heating scenario.

The novelty and scientific contributions of this paper lies in the construction of a 2016 EnergyPLAN model for Norway, a highly electrified EnergyPLAN model for Norway and the analysis of 4th generation district heating in a highly electrified energy system based on hydropower.

In the following, the methodology for the simulation and modelling is described in section 2, followed by a presentation of simulation and analysis results in section 3. Some of the important limitations of the analysis are presented and discussed in section 4, before the conclusions are presented in section 5.

2. Methodology

The purpose of the following section is to present the methodology used for the analysis presented in this paper.

2.1. Simulation tool

The basis for the work in this paper is a national energy system analysis based on simulations of the operation of the Norwegian energy system. The tool EnergyPLAN 14.0 is used to simulate the operation of the Norwegian energy system in a constructed reference scenario as well as a district heating scenario. EnergyPLAN is a deterministic input/output model seeking to optimise system operation using rule based dispatch. The simulation tool has both technical and market economic simulation strategy options. The technical simulation option seeks to minimise fuel consumption and imports in the system while covering demands, while the market economic simulation seeks to minimise short term marginal costs of the system within the hour [59]. In this paper, a technical simulation strategy has been used to simulate the operation of the Norwegian energy system for a constructed reference scenario and district heating scenario.

Needed user inputs in EnergyPLAN includes capacities for electricity and heat production technologies, storage capacities, energy demands, hourly distribution profiles for demands, variable production from renwable energy sources (RES) and external electricity market prices. Furthermore, the user can specify costs in the form of CAPEX, OPEX for the different energy system components, fuel and emission costs, as well as taxes [59]. Relevant demands, conversion and storage technologies, fuels, as well as the connection in between, are illustrated in the flowchart in Figure 1.

EnergyPLAN is chosen as the simulation tool in this analysis due to its previous use in analyses concerning smart energy systems and 4GDH. Examples of such use of the tool can be seen in [40] where the difference between third generation district heating (3GDH) and

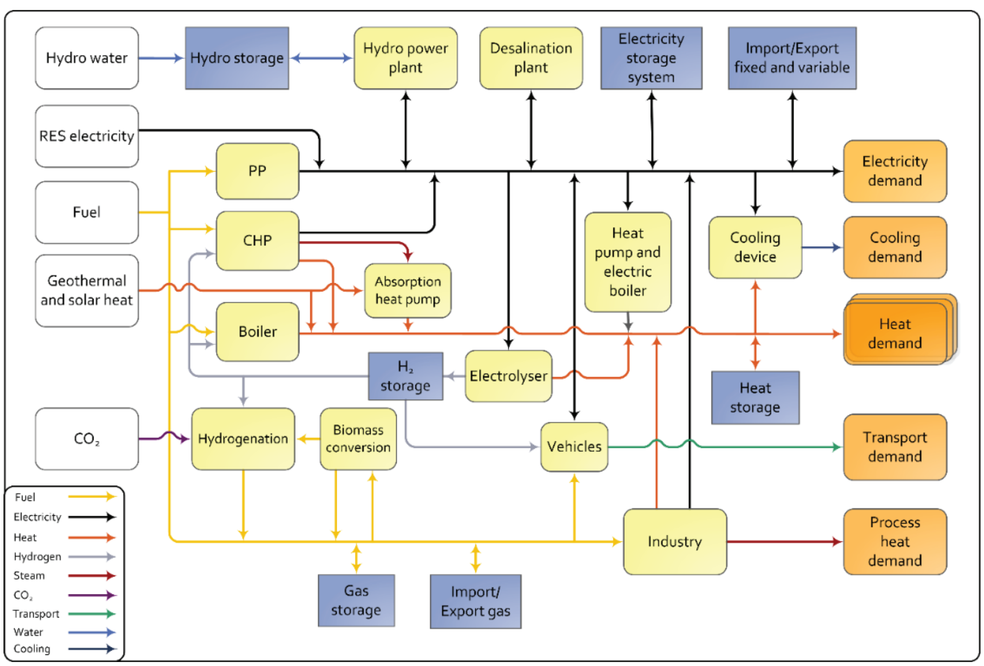

Figure 1: Inputs and connections in EnergyPLAN [59]

4GDH was investigated. In [60], Østergaard reviewed the application of the EnergyPLAN simulation tool as well as performance indicators used in these applications, comparing them to advanced energy system performance indicators. In the analysis published in 2015 it was found that EnergyPLAN had been applied in 95 analyses, mostly focused on a national level analysing the integration of renewable energy. The paper found 6 articles where EnergyPLAN had been used to analyse district heating.

2.2. Construction of a reference scenario

In order to analyse the effects of an expansion of 4GDH in a future highly electrified Norwegian energy system, a basis, or a reference, for the analysis must be established. In this paper, the basis is constructed based on several steps. This step-based approach does not create an accurate representation of how the Norwegian energy system will develop in the future, but does give the authors the opportunity to analyse how different elements and developments in the energy system affect each other and the operation of the system. A step-by-step approach also helps ensure transparency and replicability of the model. A step-by-step approach was also used by Connolly, Lund and Mathiesen in [61]. In Connolly, Lund and Mathiesen's analysis, a step-by-step approach was used for modelling the transition of the European energy system towards a 100% renewable smart energy system, and followed 5 main steps, with the first one being the a EU28 Business-as-usual reference scenario. The purpose of the analysis presented in this paper is not to create a future renewable smart energy system, and thus the steps differ from those presented in [61]. Furthermore, the composition of the Norwegian energy system differs from that of the EU28, particularly due to the large shares of hydropower resources. However, following a similar step-by-step approach is seen as a transparent approach focusing on sector by sector chosen for this analysis. For this analysis, five main steps are outlined, with the first one being step 0, a 2016 baseline model construction. The steps are outlined in Figure 2.

The resulting energy system design after step 4 is a highly electrified Norwegian energy system. However, it is not a 100% renewable system, as there are still fossil fuels present in some of the transport and industrial sector. In a smart energy systems approach as presented in [61], the final 3 steps towards a smart energy system concerns the replacement of remaining fossil fuels with biomass and synthetic fuel solutions. The consequence of leaving out the final step of renewable electrofuels is that the potential synergies between the production of electrofuels and district heating cannot be explored. Furthermore, the potential increased electricity demand for the production of electrofuels will not be reflected in the analysis.

2.2.1. Step 0: 2016 energy system model

The starting step for the analysis is the construction of a reference scenario. One of the authors of this paper has previously constructed and published a 2015 energy system model for Norway in EnergyPLAN [62], [63]. A new model for 2016 has been constructed for the purpose of the analysis in this paper. The tool chosen for

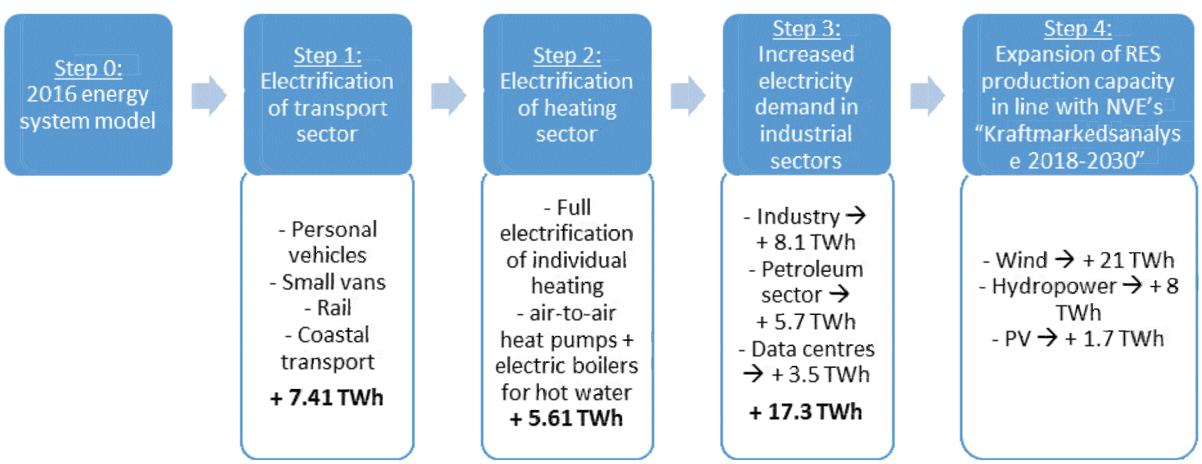

Figure 2: Schematic overview of step-approach for the design of reference scenario

simulation of the energy system includes a long range of potential inputs for electricity, heating, industry, gas and transport sectors. A comprehensive list of relevant data inputs and sources as well as important exogenously defined time series can be found in Appendix. The inputs for DH production units in the 2016 model are illustrated in Figure 3 and Figure 4, respectively.

Capacities for district heating production units are not reported in statistics, and thus, the numbers presented in Figure 4 are estimations based on the production given in Figure 3 and full load hours reported in [64].

Installed capacities for electricity generation as well as actual generation for 2016 are illustrated in Figure 5.

2.2.2. Step 1: Electrification of transport sector

For what concerns the transport sector, an assumption is made based on full electrification of personal vehicles, small vans, and railways, as well as 50% of the coastal transport demand. Electrification of large trucks and aviation is left out. An increase in efficiency of engines when going from fossil fuels to electricity in the transport is included.

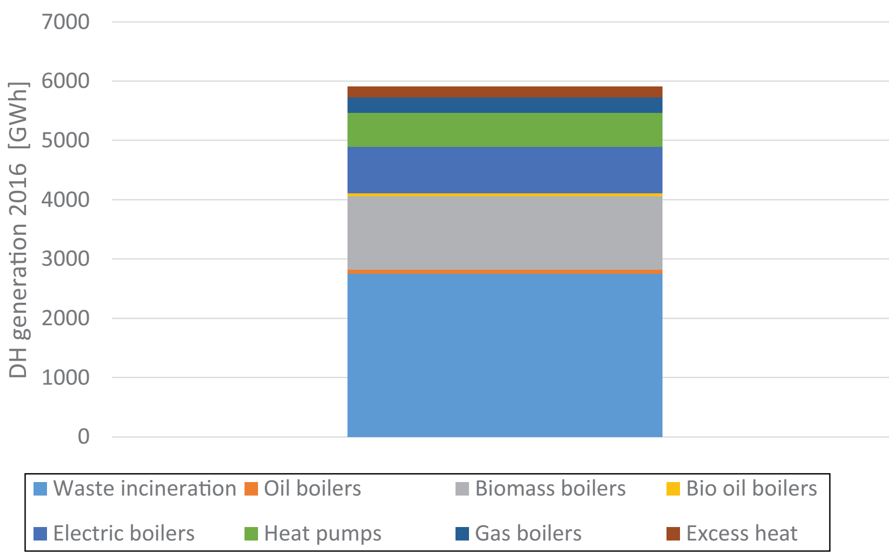

Figure 3: DH generation in 2016 based on statistics in [15]

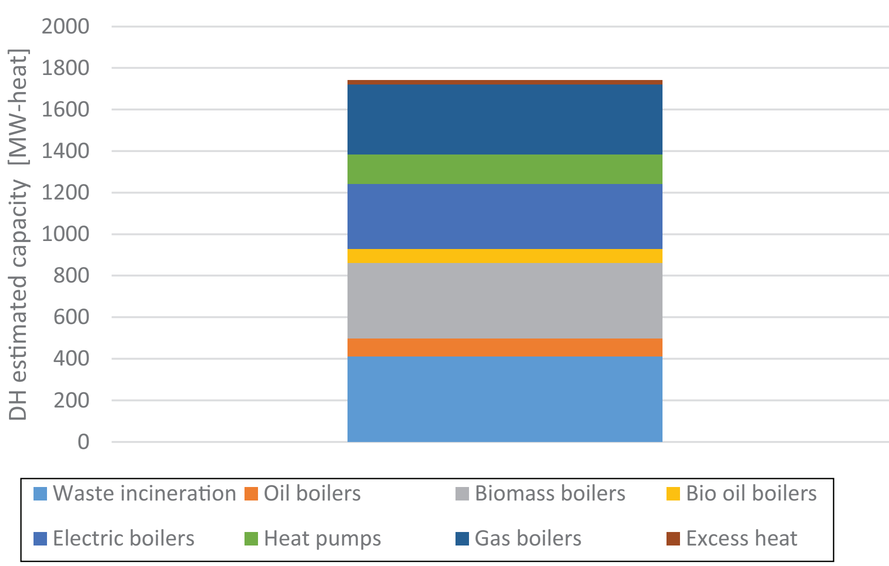

Figure 4: Estimated capacity for generation units in the DH system

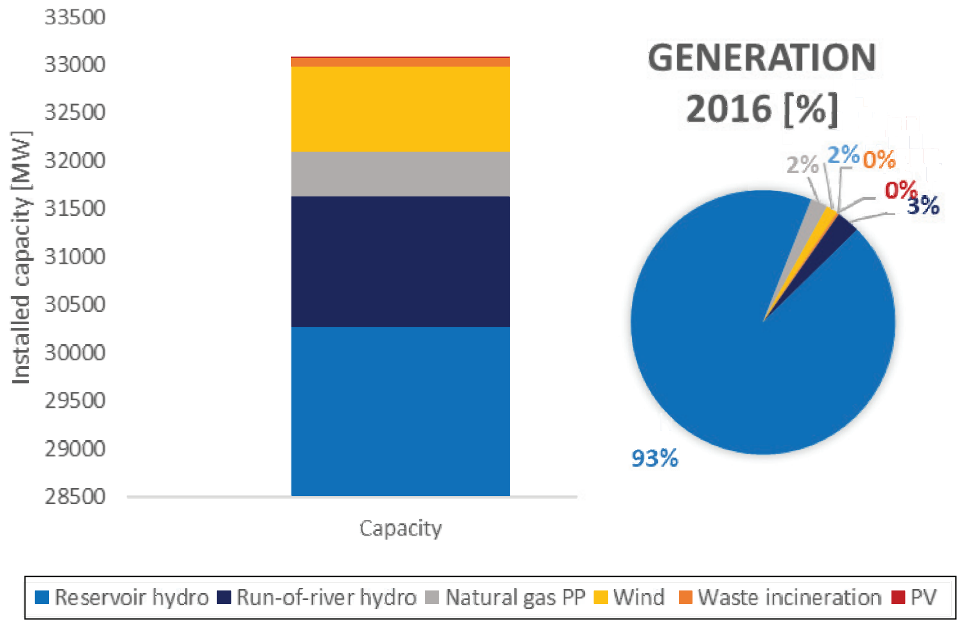

Figure 5: Capacity inputs for electricity production units in the 2016 EnergyPLAN model and generation as reported in [4]

The total estimated increase in electricity demand is calculated to 7.41 TWh, which is similar to expectations in [3], where a total increase of 7.6 TWh of electricity is expected in the transport sector.

2.2.3. Step 2: Electrification of heating sector

For step 2, it is assumed that the entire heating sector, except that covered by existing district heating and existing electric heating solutions in 2016, is electrified. This is seen by the authors as the most likely alternative to fossil fuel based heating solutions but is not based on a concrete analysis or assumption by external sources. It is assumed that 25% of the demand is for hot water demand and the remainder for space heating. Electric boilers are installed to cover the hot water demand while air-to-air heat pumps with an average coefficient of performance (COP) of 2 are assumed to cover the space heating demand. This is a simplified approach, as existing buildings with water borne systems will likely keep these and use x-water heat pump solutions. However, due to a lack of data, this simplified assumption is made.

2.2.4. Step 3: Increased electricity demand in industry sectors

It is expected that the electrification path to decrease the use of fossil fuels will dominate going forward in Norway. This includes the electrification of industrial sectors. In order to reflect this increased electricity demand, assumptions from [10] are used. It is expected that the electricity demand increase in industrial sectors will amount to 17.3 TWh in 2035. Of this, 3.5 TWh is expected to be related to new data centres placed in the country, while the remainder is related to large industry intensive projects and electrification of parts of the off-shore oil and gas sector [10].

Table 1: Increase in installed RES production capacity in step 4

Technology	Increase in yearly production [TWh] [3]	Capacity increase (calculated) [MW]
Wind	+21	+896
Hydropower	+4 (+4 in inflow)	+870
Hydro storage		*+2,488 [GWh]*
Solar	+1.7	+1,156

2.2.5. Step 4: Expansion of RES production

An expansion of electric production capacity is expected and needed to cover the increased electricity demand from electrification of the Norwegian energy system. It is expected, that a large share of the increase will be in variable renewable electricity production from wind. The assumptions for capacity increase are listed in Table 1 and are based on assumptions from [3]. As only increase in yearly production is given, an installed capacity increase is calculated by assuming the same capacity factors as in 2016. It is not specified in [3] if the increase in hydropower is regulated or unregulated. For this analysis, it is assumed that this is regulated hydropower connected to a storage. This gives a higher flexibility than unregulated hydropower in the system.

2.3. District heating expansion and 4GDH scenarios

To analyse the role of 4GDH in a highly electrified Norwegian energy system, a scenario representing a situation with district heating expansion is constructed. Though the scenario represents only a hypothetical general situation, it is decided to keep the modelled expansion within the technical district heating potential of 11.5 TWh presented in [57]. Thus, the constructed scenarios are based on an increased district heating demand of 5.6 TWh additional to the existing demand in 2016. A corresponding decrease in use of direct electric heating is implemented.

2.3.1 4GDH scenarios in the context of smart energy systems

As the purpose of this analysis is to analyse the role of 4GDH in a highly electrified hydropower based energy system, the constructed district heating scenario should reflect the characteristics of a 4GDH system. In this analysis, the characteristics of a 4GDH system modelled in EnergyPLAN is reflected in:

- Heat savings in buildings
- Higher efficiencies for heat pumps
- Low heat losses in the district heating network

Furthermore, the analysis is framed within the concept of smart energy systems. Thus, the scenario should also reflect this. The characteristic of a smart energy system having cross sector integration between the heating and electricity sector, is to some extent already present in a highly electrified Norwegian energy system with a high share of electric heating. However, the flexibility of electric heating in individual heating systems can be more limited, due to lack of alternative heating options, small storage tanks and individual heat management. To add to this, individual electric heating based on air-to-air heat pumps or direct electric heating elements heating ambient air do not have storage options. A district heating system with a large share of electric heating has a larger potential to be flexible, as there is a possibility to connect larger heat storages and execute central planning and control. A district heating system also provides flexibility due to the potential diversity of fuels to produce heat. Thus, basing a district heating expansion solely on electricity must be considered as something that is potential within the smart energy systems concept, but does not increase the diversity of the system. Alternative sources for district heating production that are or may be considered CO_2 neutral are biomass and biogas based solutions, excess heat and solar heating. However, it may be discussed whether or not biomass and biogas solutions should be used for heating purposes or in other parts of the energy system [65].

In this analysis, one district heating scenario is constructed. In the scenario, DH1, heat pumps are implemented as baseload units and electric boilers as peak load units. A heat storage capacity with the capacity to store 24 hours of average district heating demand is included to explore potential utilisation of such a storage and consequently its contribution to flexibility within the system. Such a scenario will show the differences in efficiency and flexibility between individual electric heating and electricity based district heating. Furthermore, the characteristics of a 4GDH system and smart energy system will be illustrated through higher heat pump COP and sector integration between the district heating and electricity sector. A separate analysis focused on the utilisation of excess heat is conducted within the designed scenario. The assumptions used for the scenario construction are summarised in Table 2**.**

Table 2: Assumptions for DH1 scenario

Parameter	Assumption	Unit	Reference
Increased district heating potential (without heat savings)	5.6	[TWh]	[57]
Heat savings	30	[%]	[48]
Grid losses	11	[%]	[15]
Base load share (of maximum yearly load)	60	[%]	[64]
Peak load share (of maximum yearly load)	40	[%]	[64]
Heat pump COP	3.5	[–]	[64]
Electric boiler efficiency	98	[%]	[64]
Heat storage capacity	29.4	[GWh]	

The heat pump COP is based on an assumption that the implemented heat pumps are sea water heat pumps. It should be noted that extra back-up generation is not included in the design of the DH scenario, as the need for this is not reflected in the technical simulation used for this analysis. This should however, be included in a real life system. In order to provide security of supply, back-up generation units would most likely need to be based on a different fuel than electricity, for example biomass or biogas. The increase in DH demand and production capacities are illustrated graphically in Figure 5.

In the figure, the distribution curve representing the heat demand is shown for the reference scenario and the DH1 scenario respectively. In the DH scenario, the DH demand consists of the DH demand in the reference scenario with the addition of the additional DH demand presented in Table 2. Heat savings of 30 % are applied to the additional DH demand but not to the DH demand from the reference scenario. In addition, the installed capacities for the different DH production units in the scenarios are marked in relation to the heat demand. The units are stacked in order of priority in EnergyPLAN. Thus, the lowest units such as waste incineration and excess heat are used to cover the demand first, while fuel boilers (natural gas, bio oil and oil) are the last activated units.

3. Results

In the following section, the results from the simulation of the different scenarios are presented. The presented results are focused on the effect of 4th generation DH on the electricity surplus in the country as well as the effect of implementing heat storage and larger shares of excess heat.

3.1. Electricity consumption, production and export

Simulation results showing yearly electricity demands, electricity production, and electricity export are illustrated in Figure 6.

A reduction in electricity demand can be identified in the DH1 scenario compared to the reference scenario. This demand reduction can be explained through the heat savings in buildings converted to DH as well as the higher COP of the heat pumps in 4GDH. The electricity production remains unchanged, as the production is exogenously defined by the user, also for reservoir hydropower. In EnergyPLAN, reservoir hydropower is flexible within the hours of the year, but the end and start value of the hydropower storage should be the same, thus defining the annual production proportional to the defined annual inflow to reservoirs. The consequent increase in electricity export is thus illustrating the additional

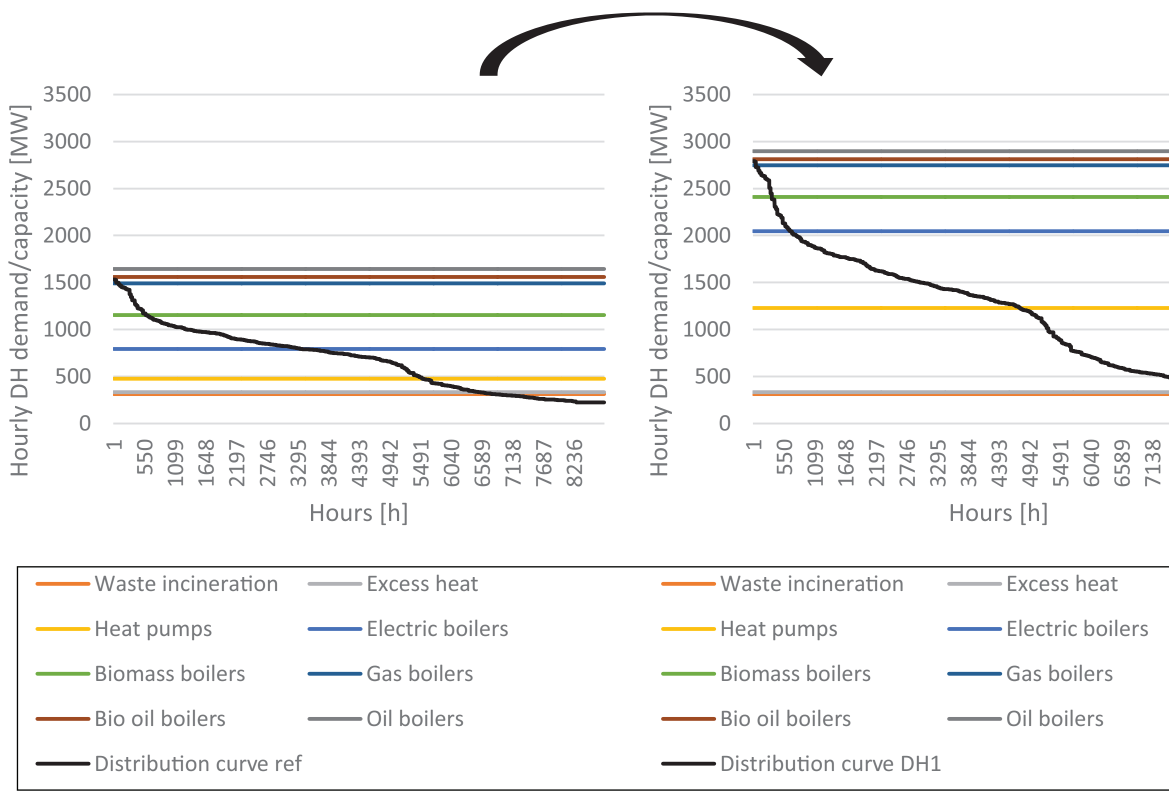

Figure 6: Distribution curves for DH demand and installed heat production capacities in the reference scenario (left) and DH1 scenario (right)

electricity surplus in Norway when introducing 4GDH. The primary energy consumption is also reduced by 0.27 TWh, indicating that the use of fuels such as biomass and gas for heat production is also reduced.

3.2. Heat storage and flexibility

In the simulation results, the implemented heat storage is not used at all throughout the year. The heat storage would normally be used to reduce fuel boiler production, however, as there is enough capacity in heat pumps and electric boilers, there is no fuel boiler production. The storage capacity is not used to move electricity based heat production. However, both short and long term fluctuations in the electricity sector are balanced through the available hydropower resources and storage capacity, as well as export through interconnections. It should however be noted, that this is the result of the logic integrated in the EnergyPLAN model in the specific technical regulation strategy as well as the limitations of the EnergyPLAN model as discussed further in section 4.2.

3.3. Excess heat utilisation

An analysis of excess heat was conducted by gradually increasing the amount of excess heat in the DH1 scenario. This was interesting to investigate as a 4GDH system allows for a larger integration of low temperature excess heat. The results from the analysis are illustrated graphically in Figure 7.

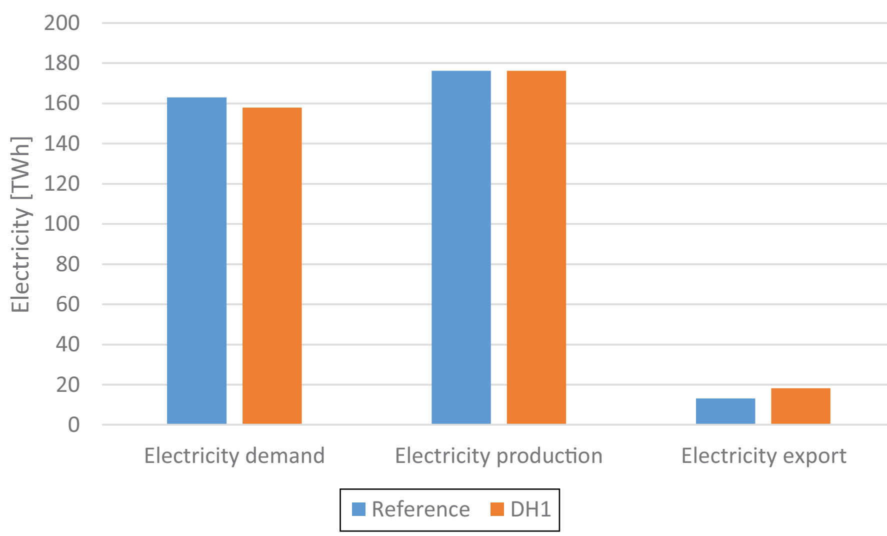

Figure 7: Simulation results fro reference and DH1 scenario related to electricity consumption, production and export

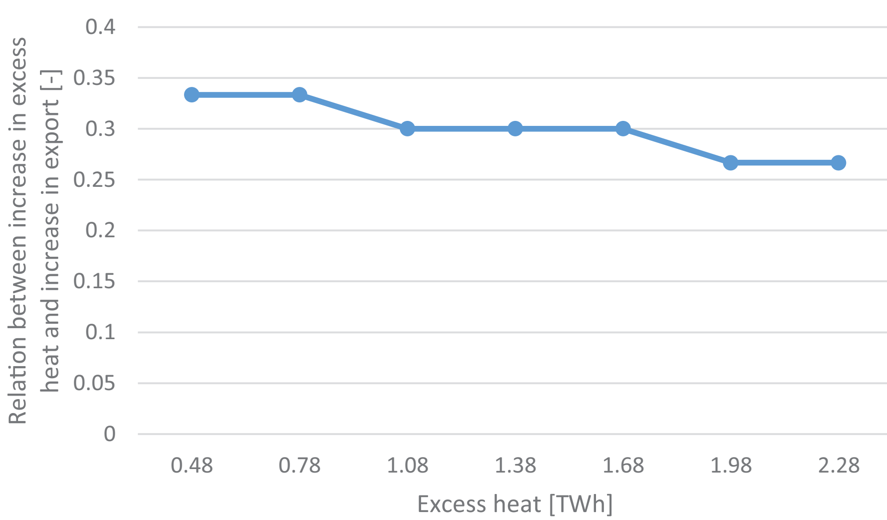

Figure 8: Relation between increase in excess heat and increase in electricity surplus for export

The relation between increase in excess heat and increase in electricity surplus is never 1:1. In the simulated cases with lower amounts of excess heat, this is almost directly linked to the efficiency of the heat pumps and electric boilers in the district heating system. It is also seen, that the relation is not linear, the larger amounts of excess heat are implemented. This is due to the difference between heat demand in summer and winter periods, and the assumption that the excess heat has a constant distribution throughout the year. Thus, at some point, there will be a waste of excess heat in the summer periods, where the baseload demand is not high enough to absorb the full excess heat potential. It should be noted, that the evaluated range for implementation of excess heat in the DH system is within the estimated potential of 10 GWh presented in [66].

3.4. Alternative scenario: heat savings and highly efficient individual heating solutions

An efficient alternative to DH-solutions are efficient individual heating solutions. It is therefore relevant to compare the analysed DH1 scenario to an individual heating scenario with heat savings and efficient heat pumps, to evaluate the actual effects of district heating compared to the effects of heat savings. For the alternative scenario it is assumed, as for the DH1 scenario, that there is a shift from individual direct electric heating to the more efficient solution. Relevant assumptions are presented in Table 3.

The heat pump COP is based on a heat pump solution using ground water or ground source heating, which are presented as the ones with the highest efficiency in [64]. However, the applicability of these can be dependent on local soil and water conditions [64], and thus other solutions such as air-to-water solutions with a lower COP might be more applicable.

The differences between the DH scenario and the alternative scenario are illustrated in Figure 9.

Even though the differences between the DH1 scenario and the alternative individual heating scenario are minimal, the DH scenario has a slightly lower electricity demand. This indicates that it is the implementation of heat savings and increased efficiencies of heat production technologies that has the largest influence on the electricity demand and electricity surplus. However, it should be noted that the DH1 scenario results presented do not include any excess heat integration. This was analysed separately in section 3.3. An individual heating scenario does not allow for the integration of excess heat, and the availability of high-temperature heat sources may be more limited. Furthermore, even though

Table 3: Inputs for alternative highly efficient individual heating scenario

Parameter	Assumption	Unit	Reference
Shifted from direct electric heating (without heat savings)	5.6	[TWh]	
Heat savings	30	[%]	[48]
Heat pump COP (new heat pumps)	2.9	[–]	[64]

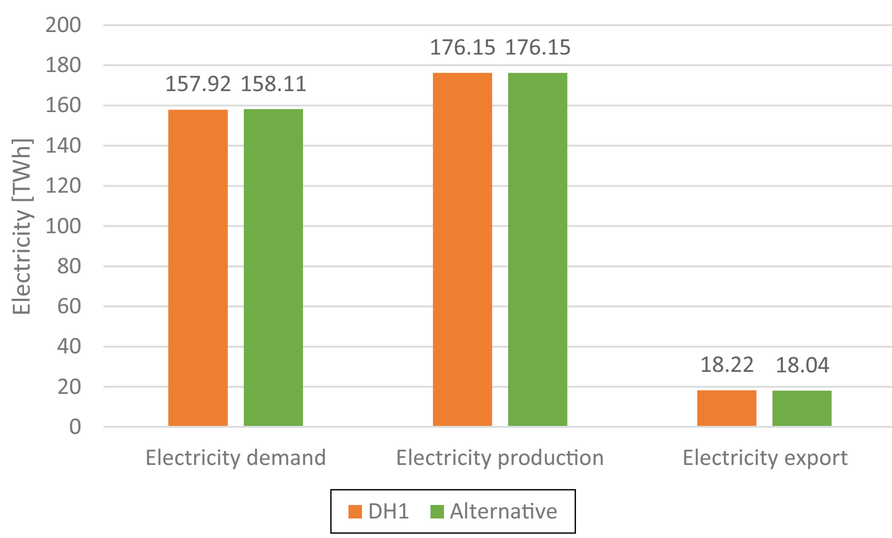

Figure 9: Simulation results for DH and alternative highly efficient individual heating scenario

the chosen simulation strategy does not utilise the implemented heat storage capacity in the DH1 scenario, this could contribute to flexibility in moving production and demands on an hourly basis, thus potentially reducing the use of electric boilers and increasing system efficiency.

4. Discussion and future work

In the following section, some of the choices and limitations of the conducted analysis are discussed. The purpose is to shed light on some of the potential uncertainties in the model affecting the analysis as well as how the choices made affect the results and consequently the conclusions hereof.

4.1. National versus local modelling

In this analysis, a national energy system analysis has been conducted. Thus, local restrictions, benefits and conditions are not necessarily reflected in the analysis. Varying local conditions are partly taken into account for what concerns the heating sector. Heat degree days are used for the construction of hourly time series for individual and district heat demands, and these degree days are distributed according to the share of population and district heating demand in the different counties of the country. Thus, they should reflect that there might be hourly differences in space heat demand in different parts of the country at the same time. However, the district heating network is modelled as one single production site and network, while in reality there were 107 different DH production companies in 2016 [13]. Thus, in reality, production units will be distributed and operated according to local demands. Consequently, the prioritisation and consequent production of different units as it is defined in EnergyPLAN will not match the actual prioritisation and generation. This is also reflected in the 2016 model, where boiler production is lower in the simulated model than reported in statistics for 2016. Adding to this, it might be that an aggregated analysis overestimates the effect of implementing district heating, as local limitations do not hinder the full use of the most efficient production units.

Furthermore, it should be noted, that even though the simulated model results mostly show an effect on the energy system related to the implemented heat savings and increased efficiency of production technologies, and not to the implementation of a district heating system in itself, there might be local advantages of district heating systems that are not reflected in the model. Such advantages may be better control of heat production demands due to central management and options for exploitation of available excess heat demands.

4.2. Uncertainties regarding data inputs and model limitations

When modelling and analysing energy systems, especially those of the future, it is important to note that models can aim to represent reality, but can never replicate reality. For the analyses in this paper, a simulation model based on predetermined operational strategies is used, and thus, the results presented are a product of the choices made by the creator of the simulation tool. Furthermore, the analyses are based on a large dataset ranging from capacities and costs for production technologies to hourly distributions for demands and production from variable RES. There is potentially a large amount of data inputs that are subject to uncertainties. It is impossible to go into the uncertainties of every single data input in the scope of this paper, but some uncertainties are worth mentioning because of their relation to the core of the analysis.

In general, there is limited data available for heat demands in Norway. The lack of data availability represents a large uncertainty in this analysis, as the data material it is based upon is often also estimations. Furthermore, EnergyPLAN operates with capacities for production units as inputs, while available statistics are reported in annual production. Thus, capacities, especially for DH production units, are only estimations based on estimated full load hours reported in [64].

In the analysis it is chosen to assume the same hourly distribution for variable RES, hydropower inflow, and heat and electricity demands in the reference and DH1 scenario as in 2016. This is done, as a modelling of future unknown distributions are considered out of the scope of this analysis. However, in reality, these distributions might be subject to change due to changed weather patterns, changed electricity consumption patterns for new and existing electricity consumers and changed heat demand patterns due to heat saving measures.

The chosen simulation tool, EnergyPLAN, uses rule based pre-defined dispatch strategies to simulate the energy system. If electric boilers are modelled as electric boilers in EnergyPLAN, they will be prioritised below fuel boilers and will only be used when there is electricity surplus in the system. Thus, they will not be used as peak load boilers. It has therefore been chosen to model the electric boilers as heat pumps with a COP of 1 and define an average COP based on the shares of production presented in Table 2. This has the consequence, that the storages are not used to reduce or move production from electric boilers. In the results presented in section 3.2, it was found that the storage capacity implemented in the DH scenario was not used, which is related to the logic implemented in the simulation tool. In order to better reflect the advantages of storage capacity in the DH system when implementing electric boilers for peak capacity, it should be evaluated if future analyses are best conducted in the EnergyPLAN simulation tool.

4.3. Economic feasibility

This analysis has not included any economic considerations. However, the potential expansion of 4GDH in Norway will be dependent on the economic feasibility of such an expansion. The additional electricity surplus can generate an income revenue for producers when sold at high electricity prices, and the interest in using hydropower resources to balance fluctuations in the European energy system is very much an economic interest, to increase revenue for the hydropower producers. The economic interest in expansion of 4GDH to increase electricity surplus or reduce installed electricity production capacity is therefore dependent on the alternative cost for investments in district heating and revenue from potential increased flexibility in the system to maximize export revenues and minimize heat production costs. To simulate this, a market economic simulation strategy should be used, to minimize short term heat and electricity production costs and maximize water value for reservoir hydropower.

5. Conclusion

An expansion of 4GDH in a highly electrified energy system can increase the total system efficiency, and consequently reduce the need for electric production capacity expansion or increase the potential electricity export. However, in the conducted analysis the effects are only seen in relation to the characteristics of a 4GDH system specifically, such as the introduction of heat savings in buildings and more efficient heat production technologies, and not the switch from individual to district heating as such. This is also illustrated in a comparison to an alternative scenario with highly efficient heat pump solutions and heat savings in individual heating systems, which show very similar effects as the designed 4GDH system. The modelled large scale heat storages are not utilised in the simulation of the DH system, due to the logic behind the chosen simulation tool. Thus, the positive effects of 4GDH may be underestimated. In the simulated systems, the flexibility is still largely found in the reservoir hydropower resources, which together with interconnections ensures a balance between supply and demand of electricity.

An introduction of 4GDH will allow for a larger integration of low temperature excess heat potential, which can additionally increase the system efficiency. This is not possible in a system based on individual heating solutions. However, due to a low district heating demand during summer and high peaks during winter, as well as a high efficiency of heat pumps as the alternative, the potential to utilise excess heat to its full potential is limited. This is reflected in a non-linear rate of substitution of electricity use when introducing larger shares of excess heat in the system.

Acknowledgements

This article was invited and accepted for publication in the special issue on the 5th International Conference on Smart Energy Systems in Copenhagen 10-11 September 2019 in the International Journal for Sustainable Energy Planning and Management [67].

The work presented in this paper is a result of research activities related to the projects «Renewable Energy Investment Strategies – A two dimensional interconnectivity approach (RE-Invest)» and «Renewable Energy Projects: Local Impacts and Sustainability (RELEASE)». These projects have received funding from Innovation Fund Denmark under Grant No. 6154-00022B and from the Research Council of Norway under project number 238281 respectively.

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